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Comparison of ISO 6336 and AGMA 2001 Load Capacity Ratings for Wind Turbine Gears

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INTRODUCTION

Because wind turbine gears are manufactured and used worldwide, both European and American industrial standards are used for rating load capacity.

Many European manufacturers such as Flender, Hansen, and Valmet use DIN 3990 [1] to rate wind turbine gears. DIN 3990 has not been updated in 13 years and is available only in German. Software [2] for rating per DIN 3990 is available from the German Gear Manufacturers Association, FVA.

DIN 3990 is specified in Germanischer Lloyd Rules and Regulations [3]. Det Norske Veritas uses the Norwegian Classification Note 41.2 [4,5].

Over the past 44 years, many countries including the United States have developed the gear rating standard ISO 6336 [6,7,8,9]. It was finally published in 1996, but only in limited form. Section 4, which covers scuffing, is published only as drafts [10,11]. ISO 6336 is in English, and software based on ISO 6336 can be purchased from the AGMA [12].

Ultimately, ISO 6336 [6,7,8,9] will probably be used by most countries except the United States where AGMA 2001 [13] will probably be used for many years. Therefore, there is a need for the AGMA Wind Turbine Committee to include guidelines for gear rating in accordance with ISO 6336 and AGMA 2001 in AGMA/AWEA 6006-AXX [14]. However, research by many investigators [15,16,17] has shown that ISO 6336 and AGMA 2001 can give significantly different ratings. These differences must be addressed to obtain reliable guidelines.

Variations between ISO 6336 and AGMA 2001 ratings are due to differences between numerous parameters that influence gear rating and differences in engineering models.

ISO 6336 and AGMA 2001 use similar analytical models to calculate load capacity based on macropitting resistance. However, the two standards can give different ratings as demonstrated by McVittee [18] who showed wind turbine gears rated by the two methods differed significantly in rated macropitting load capacity.

ISO 6336 and AGMA 2001 use fundamentally different models to calculate load capacity based on bending fatigue. Comparison studies [15,16,17] have shown that ISO 6336 and AGMA 2001 give different trends for the influence of profile shift on bending stress. ISO 6336 is relatively insensitive to profile shift, whereas AGMA 2001 shows a strong effect of profile shift on load capacity. This fundamental problem remains unresolved.

ISO 6336 does not provide a method for scuffing resistance. Two methods given in ISO draft technical reports are the Total Contact Temperature method (TCT) ISO TR 13989-1 [10], and the Integral Temperature Method (ITM) ISO TR 13989-2 [11]. Errichello and Muller [19] and Polder [20] have shown that the ITM is misleading and unreliable.

Based on progress to date, it is likely that decades will pass before ISO 6336 adopts an official method for calculating scuffing resistance. AGMA recommends the TCT method for assessing scuffing risk in Annex A of AGMA 2001.

Currently, there is no recognized analytical method to assess micropitting risk. However, Errichello [21] gives guidelines developed from experiments and inspections of laboratory and industrial gears to help engineers design gears with increased micropitting resistance.

OBJECTIVE

This study summarizes load capacity ratings for actual wind turbine gears. It compares ratings obtained from ISO 6336 with those obtained from AGMA 2001.

SCOPE

Spur, low-contact ratio (LCR) helical gears, and conventional helical gears are analyzed for durability and bending strength. Scuffing resistance is not considered because ISO 6336 offers no method. Sun/planet low-speed (LS), intermediate (INT), and high-speed (HS) gearsets are considered.

Table 1 shows the twelve planetary gearsets. Nine examples are spur gears. Examples 15 and 18 are LCR helical gears with axial contact ratio $m_F < 1.0$, and example 12 is a conventional helical gearset with $m_F > 1.0$.

Table 1- Planetary gear data

Ident. No.	Power (kW)	Rotor speed (rpm)	Number of teeth			Normal module mn	Normal pressure angle (deg)	Helix angle (deg)	Center distance a (mm)	Face width b (mm)	profile shift x1
			Z1	Z2	Z3						
1											
2	50	64	23	34	91	3.175	25	0	90.4875	68.275	0
3											
4	80	90	21	26	72	4	20	0	96	66	0.1810
5	150	47	21	30	82	5	20	0	130	95	0.3330
6	250	60	16	28	74	6	20	0	139	104	0.7370
7	250	47.9	21	36	93	7	20	0	205	100	0.4600
8											
9											
10											
11	600	30	18	28	75	11	20	0	266	183	0.7400
12	660	30	19	41	101	9	20	8.2222	280	199.6	0.3470
13	660	24.1	22	39	101	9	20	0	284	200	0.5600
14	660	30	18	34	87	11	20	0	301	185.6	0.7931
15	660	30	27	48	123	8	20	4.0000	302	203	0.1609
16											
17	750	28.5	16	26	68	14	20	0	309	260	0.7540
18	750	22.4	21	39	99	10	20	7.4947	308	210	0.1850

Table 2 shows the six examples of HS and INT gearsets. The first four examples are single-helical gearsets and examples h25 and h30 are double-helical gearsets.

Table 2- Helical gear data

Ident. No.	Power (kW)	Pinion speed (rpm)	Number of teeth		Axial contact ratio mF	Normal module mn	Normal pressure angle (deg)	Helix angle (deg)	Center distance a (mm)	Face width b (mm)	Profile shift X1
			Z1	Z2							
h1											
h2											
h3											
h4											
h5											
h6											
h7											
h8	660	526	25	83	1.18	7	20	8	382	186	0.0409
h9											
h10											
h11											
h12	375	180	25	151	1.93	7	25	12	630	204	0.2500
h13											
h14											
h15	660	1812	25	83	2.2	4.5	20	15	255	120	0.2500
h16											
h17											
h18											
h19	600	1519	26	71	2.07	5	20	19	262	100	0.4939
h20											
h21											
h22											
h23											
h24											
h25	600	1525	25	99	4.78	4.5	20	25	310	160	0.3210
h26											
h27											
h28											
h29											
h30	750	1215	23	162	6.84	4	20	30	430	172	0.3349

RATING STANDARDS

All gearsets were rated in accordance with ISO 6336 [6,7,8,9] and AGMA 2001 [13].

SOFTWARE

All gearsets were rated using the ISO 6336 computer program [12] and the AGMA218 computer program [22]. Gear and hob geometries were calculated with the GEARCALC computer program [23].

RATING PARAMETERS

To obtain rating comparisons independent of derating factors, input data for the ISO 6336 and AGMA218 computer programs were prepared with the same derating factors for application, load distribution, and dynamics.

The same gear geometry was used for both programs. Hob geometry was the same except hob addendum h_{apo} was adjusted for the ISO 6336 program to obtain correct root diameters.

Material grades and hardnesses were selected to give similar allowable stresses as shown in Table 3.

Table 3- Allowable stresses		
Rating standard	Durability (MPa)	Strength (MPa)
ISO 6336	$\sigma_{Hlim} = 1500$	$\sigma_{Hlim} = 500$
AGMA 2001	$S_{ac} = 1551$	$S_{at} = 483$

Lower curves for life factors were selected to obtain ratings consistent with twenty-year design life and no pitting allowed.

ISO 6336 input data were as follows:

Hob geometry, d_{a1}, d_{a2}, x_2, us, δ_0 from GEARCALC

$h_{apo} = h_{a0} + \Delta s_n/(2*\tan\alpha_n)$
h_{a0} from GEARCALC
Δs_n from GEARCALC

Case hardness 58 HRC
Core hardness > 30 HRC
Material grade MQ
Z_N, Y_N from lower curves and L = 175,000 hours
K_A = 1.3
$K_{H\beta}$ = 1.3 for planetary gearsets, $K_{H\beta}$ = 1.25 to 1.27 for helical gearsets
$K_{H\alpha}$ = calculated by ISO 6336
$K_{F\beta}$ = calculated by ISO 6336
$K_{F\alpha}$ = calculated by ISO 6336
K_V = calculated by ISO 6336

AGMA218 input data were as follows:

Hob geometry, d_{a1}, d_{a2}, x_2, us, δ_0 from GEARCALC (same as ISO 6336 input)
Hardness 654 HB
Material grade 2

Power rating using lower curves and L = 175,000 hours
$C_a = K_A = 1.3$
$C_m = K_{H\beta}$ for durability ($K_{H\beta}$ from ISO 6336)
$C_V = 1/(K_V * K_{H\alpha})$ for durability (K_V, $K_{H\alpha}$ from ISO 6336)
$C_m = K_{F\beta}$ for strength ($K_{F\beta}$ from ISO 6336)
$C_V = C_m/(K_V * K_{F\beta} * K_{F\alpha})$ for strength (K_V, $K_{F\beta}$, $K_{F\alpha}$ from ISO 6336)

RATED LOAD CAPACITY

Safety factors are defined as follows:

For ISO 6336 Durability

$$SH_{ISO} = \frac{\sigma_{HP}}{\sigma_H}$$

Where σ_{HP} and σ_H are as defined in ISO 6336-2 [7] and $S_{Hmin} = 1.0$.

For ISO 6336 Strength

$$SF_{ISO} = \frac{\sigma_{FP}}{\sigma_F}$$

Where σ_{FP} and σ_F are as defined in ISO 6336-3 [8] and $S_{Fmin} = 1.0$.

For AGMA 2001 Durability

$$SH_{AGMA} = \left(\frac{P_{ac}}{P}\right)^{1/2}$$

Where P_{ac} and P are as defined in AGMA 2001 [13] and $S_H = 1.0$.

For AGMA 2001 Strength

$$SF_{AGMA} = \frac{P_{at}}{P}$$

Where P_{at} and P are as defined in AGMA 2001 [13] and $S_F = 1.0$.

Allowable Torque Ratio compares the allowable torque according to AGMA 2001 to the allowable torque according to ISO 6336. It is defined as follows:

For Durability

$$\frac{Ta}{Ta_{ISO}} = \left(\frac{SH_{AGMA}}{SH_{ISO}}\right)^2$$

For Strength

$$\frac{Ta}{Ta_{ISO}} = \left(\frac{SF_{AGMA}}{SF_{ISO}}\right)$$

Allowable Torque Ratios for $Z_N = Y_N = 1.0$ are defined as follows:

For Durability

$$\left(\frac{Ta}{Ta_{ISO}}\right)_{ZN=1} = \left(\frac{SH_{AGMA}}{SH_{ISO}}\right)^2 \times \left(\frac{ZN_{ISO}}{ZN_{AGMA}}\right)^2$$

Where ZN_{ISO} is Z_N defined in ISO 6336-2 [7] and ZN_{AGMA} is Z_N defined in AGMA 2001 [13].

For Strength

$$\left(\frac{Ta}{Ta_{ISO}}\right)_{YN=1} = \left(\frac{SF_{AGMA}}{SF_{ISO}}\right) \times \left(\frac{YN_{ISO}}{YN_{AGMA}}\right)$$

Where YN_{ISO} is Y_N defined in ISO 6336-3 [8] and YN_{AGMA} is Y_N defined in AGMA 2001 [13].

DISCUSSION OF RATINGS FOR PLANETARY GEARS

Appendix A gives a table and figures that summarize results of all ratings.

Figures 1 and 2 show safety factors according to ISO are greater than those according to AGMA 2001 for all planetary gearsets. The range and average values of safety factors are summarized in Table 4.

Table 4- Summary of safety factors for planetary gears

Figure No.	Standard	Criteria	Gear type	Safety factor	Value range	Value average
1	ISO 6336	Durability	All	SH	0.86 to 1.30	1.11
1	AGMA 2001	Durability	All	SH	0.68 to 1.04	0.87
1	ISO 6336	Durability	Spur	SH	0.86 to 1.23	1.07
1	AGMA 2001	Durability	Spur	SH	0.68 to 0.99	0.82
2	ISO 6336	Strength	All	SF	1.36 to 2.45	1.87
2	AGMA 2001	Strength	All	SF	0.77 to 1.61	1.16
2	ISO 6336	Strength	Spur	SF	1.36 to 2.45	1.92
2	AGMA 2001	Strength	Spur	SF	0.77 to 1.61	1.14

The allowable torque ratio in Figure 3 is normalized for ISO 6336 rating. Therefore, only one bar is necessary to show durability and strength ratings for ISO 6336. The range and average values of allowable torque ratios are summarized in Table 5.

Table 5- Summary of allowable torque ratios for planetary gears

Figure No.	Standard	Criteria	Gear type	Value range	Value average
3	AGMA 2001	Durability	All	0.56 to 0.67	0.61
3	AGMA 2001	Durability	Spur	0.56 to 0.64	0.59
3	AGMA 2001	Strength	All	0.56 to 0.77	0.62
3	AGMA 2001	Strength	Spur	0.56 to 0.66	0.59

Figure 4 is similar to Figure 3 except the allowable torque ratio is calculated for life factors $Z_N = Y_N = 1.0$. By comparing Figures 3 and 4 and Tables 5 and 6, one can see the influence that life factors have on allowable torque ratio. There is a significant effect on AGMA 2001 durability and relatively minor effect on AGMA 2001 strength.

Table 6- Summary of allowable torque ratios for ZN = YN = 1.0

Figure No.	Standard	Criteria	Gear type	Value range	Value average
4	AGMA 2001	Durability	All	0.84 to 1.01	0.92
4	AGMA 2001	Durability	Spur	0.84 to 0.97	0.91
4	AGMA 2001	Strength	All	0.59 to 0.80	0.64
4	AGMA 2001	Strength	Spur	0.59 to 0.68	0.61

DISCUSSION OF RATINGS FOR HELICAL GEARS

Figures 5 and 6 show safety factors according to ISO are greater than those according to AGMA 2001 for all helical gearsets. The range and average values of safety factors are summarized in Table 7.

Table 7- Summary of safety factors for helical gears

Figure No.	Standard	Criteria	Helix angle (deg)	Safety factor	Value range	Value average
5	ISO 6336	Durability	< 15	SH	1.16 to 1.20	1.18
5	AGMA 2001	Durability	< 15	SH	0.96 to 0.98	0.97
5	ISO 6336	Durability	≥ 15	SH	1.18 to 1.55	1.31
5	AGMA 2001	Durability	≥ 15	SH	0.89 to 1.16	0.98
6	ISO 6336	Strength	< 15	SF	1.33 to 1.65	1.49
6	AGMA 2001	Strength	< 15	SF	1.04 to 1.09	1.06
6	ISO 6336	Strength	≥ 15	SF	1.53 to 2.74	1.98
6	AGMA 2001	Strength	≥ 15	SF	0.87 to 1.67	1.23

The allowable torque ratio in Figure 7 is normalized for ISO 6336 rating. Therefore, only one bar is necessary to show durability and strength ratings for ISO 6336. The range and average values of allowable torque ratios are summarized in Table 8.

Table 8- Summary of allowable torque ratios for helical gears

Figure No.	Standard	Criteria	Helix angle (deg)	Value range	Value average
7	AGMA 2001	Durability	< 15	0.63 to 0.71	0.67
7	AGMA 2001	Durability	≥ 15	0.55 to 0.57	0.56
7	AGMA 2001	Strength	< 15	0.63 to 0.82	0.72
7	AGMA 2001	Strength	≥ 15	0.57 to 0.68	0.62

Figure 8 is similar to Figure 7 except the allowable torque ratio is calculated for life factors $Z_N = Y_N = 1.0$. By comparing Figures 7 and 8 and Tables 8 and 9, one can see the influence that life factors have on allowable torque ratio. There is a significant effect on AGMA 2001 durability and relatively minor effect on AGMA 2001 strength.

Table 9- Summary of allowable torque ratios for ZN = YN = 1.0

Figure No.	Standard	Criteria	Helix angle (deg)	Value range	Value average
8	AGMA 2001	Durability	< 15	0.96 to 1.03	0.99
8	AGMA 2001	Durability	≥ 15	0.90 to 0.91	0.90
8	AGMA 2001	Strength	< 15	0.67 to 0.85	0.76
8	AGMA 2001	Strength	≥ 15	0.63 to 0.74	0.68

INFLUENCE OF LIFE FACTORS

Differences in ratings caused by differences in life factors can be seen by comparing life factors for N = 10^{10} cycles:

$$\frac{Ta}{Ta_{ISO}} \propto \left(\frac{ZN_{AGMA}}{ZN_{ISO}}\right)^2 \propto \left(\frac{0.68}{0.85}\right)^2 = 0.64$$

$$\frac{Ta}{Ta_{ISO}} \propto \left(\frac{YN_{AGMA}}{YN_{ISO}}\right) \propto \left(\frac{0.80}{0.85}\right) = 0.94$$

Therefore, the difference between ISO 6336 and AGMA 2001 durability ratings is largely due to differences in life factors Z_N. Durability ratings for the two standards are similar only for $Z_N = 1.0$, corresponding to 5 x 10^7 cycles for ISO 6336 and 10^7 cycles for AGMA 2001. However, wind turbine gears must be designed for twenty-year service corresponding to 10^9 to 10^{10} cycles. Therefore, lives corresponding to $Z_N = 1.0$ are too short for wind turbines and it is unreasonable to compare ratings with $Z_N = 1.0$.

Life factors for ISO 6336 and AGMA 2001 strength ratings are similar. Therefore, differences in strength ratings are primarily due to factors other than the life factors.

INFLUENCE OF PROFILE SHIFT

Figure 9 shows the results of analyzing examples 5 through 10 from Castellani [15] with the ISO 6336 [12] and AGMA218 [22] computer programs. Profile shift was varied over the range:

$$0.1642 \leq x1 \leq 1.0$$

To isolate the effects of profile shift on gear strength, factor K_x [17] is defined as follows:

$$K_x = \frac{J}{J_{x1min}}$$

Where:

$$J = \text{gear strength geometry factor}$$

$$J_{x1min} = \text{gear strength geometry factor for } x1 = 0.1642$$

Figure 9 shows AGMA 2001 is very sensitive to profile shift whereas ISO 6336 has negligible response. At x1 = 1.0 the AGMA K_x for the pinion is $K_x = 1.46$ (46% increase in strength due to profile shift). In contrast, the ISO K_x for the pinion shows a 1% <u>decrease</u> in strength ($K_x = 0.99$).

Similar divergence is obtained for the gear (AGMA K_x = 0.72, ISO K_x = 0.99 for x1 = 1.0).

Insensitivity of ISO 6336 to profile shift, and the trend for decreasing bending strength for x1 > 0.5, are not plausible and are inconsistent with experience.

Divergence between ISO 6336 and AGMA 2001 bending strength with increasing profile shift is important because most wind turbine gears are designed with profile shift. Figure 9 demonstrates that differences between ISO 6336 and AGMA 2001 depend on profile shift. Therefore, there is no constant factor for converting between ISO 6336 and AGMA 2001 bending strength ratings.

Modern analytical techniques [24] can be used to improve the engineering models of ISO 6336 and AGMA 2001 to assimilate the two methods for gear rating. Therefore, ISO 6336 and AGMA 2001 rating methods should be improved such that both methods give similar ratings. This should be done before AGMA/AWEA 6006 [14] specifies rating by both methods.

RATING FOR SCUFFING RESISTANCE

Gear scuffing failures in wind turbines have demonstrated that scuffing resistance is an important criterion for wind turbine gears. However, ISO 6336 has no official method for rating scuffing resistance. Annex A of AGMA 2001 [13] and AGMA 925-AXX [25] recommend the TCT method, which is similar to the method described in ISO TR 13989-1 [10]. Experience has shown the TCT method is reliable for assessing scuffing risk. Therefore, AGMA/AWEA 6006 [14] should specify one rating method for scuffing resistance based on the TCT method.

CONCLUSIONS

1. Safety factors for ISO 6336 are larger than safety factors for AGMA 2001 for all eighteen examples of wind turbine gears.
2. For spur gears, allowable torque for AGMA 2001 is about 59% of the allowable torque for ISO 6336 for durability and strength.
3. For helical gears with $\beta < 15°$, allowable torque for AGMA 2001 is about 67% of the allowable torque for ISO 6336 for durability, and about 72% for strength.
4. For helical gears with $\beta \geq 15°$, allowable torque for AGMA 2001 is about 56% of the allowable torque for ISO 6336 for durability, and about 62% for strength.
5. The difference between ISO 6336 and AGMA 2001 durability ratings is largely due to differences in life factors Z_N. Durability ratings for the two standards are similar only for $Z_N = 1.0$.
6. Lives corresponding to $Z_N = 1.0$ are too short for wind turbines and it is unreasonable to compare ratings with $Z_N = 1.0$.
7. Life factors for ISO 6336 and AGMA 2001 strength ratings are similar. Therefore, differences in strength ratings are primarily due to factors other than the life factors.
8. AGMA 2001 is very sensitive to profile shift whereas ISO 6336 has negligible response. Insensitivity of ISO 6336 to profile shift, and the trend for decreasing bending strength for $x1 > 0.5$, are not plausible and are inconsistent with experience.
9. There is no constant factor for converting between ISO 6336 and AGMA 2001 bending strength ratings.
10. Modern analytical techniques can be used to improve the engineering models of ISO 6336 and AGMA 2001 to assimilate the two methods for gear rating.
11. ISO 6336 and AGMA 2001 rating methods should be improved such that both methods give similar ratings. This should be done before AGMA/AWEA 6006 specifies rating by both methods.
12. AGMA/AWEA 6006 should specify one rating method for scuffing resistance based on the TCT method.

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